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6. AUTHOR(S)
Dr. Paul D. Orkwis

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Cincinnati
Dept. AsE&EM, M.L. 70
Cincinnati, OH 45221-0070

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Vortices about the leeward side of cones at incidence become asymmetric past a critical incidence ratio. They consequently produce large side forces that lead to in flight control and maneuverability problems. The origins of this asymmetry have yet to be fully understood. Questions exist as to the nature of the asymmetry instability, the bifurcation process that occurs as the solution transitions from symmetric to asymmetric, and the numerical requirements for its computation. The reported research was initiated to seek answers to these questions.

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A Study of Asymmetric Vortex Shedding Behind Missiles at High Angle of Attack Using Dynamic Solution Adaptive Meshes

Final Technical Report

by

Dr. Paul D. Orkwis

October 9, 1995

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Problem Statement

Vortices about the leeward side of cones at incidence become asymmetric past a critical incidence ratio. They consequently produce large side forces that lead to in flight control and maneuverability problems. The origins of this asymmetry have yet to be fully understood. Questions exist as to the nature of the asymmetry instability, the bifurcation process that occurs as the solution transitions from symmetric to asymmetric, and the numerical requirements for its computation. The reported research was initiated to seek answers to these questions.

Summary of Important Results

Research was conducted into the bifurcation process that leads to vortex asymmetry about cones at incidence. Computational studies employing the conical Navier-Stokes equations were employed. Numerical issues, such as algorithm symmetry, factorization error, flux limiters, grid resolution and grid symmetry were addressed. Physical issues such as flow field topology and the transition process from symmetric to asymmetric flow were examined. The validity of the conical assumption was evaluated through comparison with the experimental data of Lowson and Ponton. Lastly, a spatio-temporal stability analysis was initiated to determine the nature of the instability.

The grid studies demonstrated that numerical diffusion caused by poor grid point resolution invokes an asymmetry suppression mechanism similar to that of physical viscosity. In addition, the location of the grid point density is a significant factor in the formation/suppression of asymmetries. Symmetry breaking was linked to proper resolution of the primary leeward side saddle point and to the secondary vortex/saddle point regions. The primary saddle point was also found to be important in the transient process from the symmetric to asymmetric solutions, as discussed in later paragraphs. These findings make previous three-dimensional results suspect because of the inherent lack of resolution in three-dimensional calculations.

An approach to prove algorithm asymmetry that employs the MACSYMA symbolic manipulation software was developed and employed on the algorithm used in this study. The code was found to be analytically symmetric to roundoff error accuracy. Vortex asymmetries were computed with both this algorithm and an asymmetric modification. They were attributed to roundoff error perturbations in the former case

and to factorization errors in the latter. This finding is significant because it is the first to report vortex asymmetries computed with an algorithm proven to be symmetric.

Asymmetries were computed both with and without flux limiters. It was found that solutions made without limiters were more susceptible to asymmetry than solutions obtained with limiters. Symmetry breaking occurred on coarser meshes without limiters contrary to previously reported results. This behavior is attributed to the diffusive effects of limiters and is consistent with the numerical diffusion suppression mechanism.

The sensitivity of the solutions to perturbations was highlighted by the convergence rate behavior found with symmetric grids constructed outside and inside the code (i.e. half the grid was computed and half was formed from symmetry considerations). The now classic residual plots of Siclari and Marconi illustrate an initial residual reduction to levels slightly above machine zero with a symmetric interim solution. This is followed by a residual increase and eventual decrease to machine accuracy with an asymmetric solution. Symmetric grids formed outside the code and input with less than machine accurate read-in caused the residual to begin increasing at higher values, which indicates a higher level of perturbation. However, the final asymmetric results for the external and internal grids did not differ by an amount greater than the grid read-in error. Subsequent perturbation studies illustrated similar results in that the residual rise would begin at higher values in the perturbed cases but the final solutions would differ by an amount no greater than the perturbation. These results support the efforts of previous researchers who computed asymmetric three-dimensional solutions with the aid of surface or freestream perturbations.

The transient solution was studied both with and without perturbations and with local timestepping or time accuracy. Results for all approaches were similar in that they followed the same path from symmetric to asymmetric. This supports the contention that these phenomena can be computed by employing perturbations and a local timestepping procedure. On the other hand, perturbed coarse grid runs did not result in final solutions like those obtained on finer grids.

The topology of the flow field was studied to gain insight into the transition process from the interim symmetric to final asymmetric solution. Fluid was found to cross the symmetry plane when vortex asymmetries were present, similar to that reported by previous experimental observations. The current results found that the transient process from symmetric to asymmetric solution requires a "reformation" of the

primary saddle point. The separatrix is in effect pinched to allow flow to cross the symmetry plane. Streamlines in quadrants II and IV (figure 13, technical report 2) will, for example, move toward the saddle point while those in I and III will move away (or vice versa depending on the orientation of the asymmetry). This motion is somehow linked to the secondary vortex/saddle points in a way not currently understood, but implied by the importance of proper grid point resolution for these regions. This suggests a potential approach to controlling the asymmetry that has not been fully explored. Further investigation of this phenomena, particularly with three-dimensional calculations, is required.

Topology studies would be considered useless if not based on physically valid solutions. This validation was obtained for the conical solutions by considering the transition process that occurs as the cone is pitched in a quasi-steady fashion. The steady flow data of Lowson and Ponton were used for this purpose. The conical solutions were judged accurate because they contained all the topological features reported in the experimental results for a range of incidence angle. These conditions include zero incidence, low incidence with no crossflow separation, symmetric crossflow separation with no saddle point, symmetric crossflow separation with a saddle point and asymmetric crossflow separation. The proper topology were obtained for exactly the incidence ratios reported in the experiments. The only condition not computed accurately was asymmetric crossflow separation with three steady vortices. This is important because it is the condition at which the flow is no longer reported to be conical, hence a conical simulation would not be expected to compute it accurately.

Finally, a study of the nature of the instability was initiated through the use of spatio-temporal stability analysis. In this approach a dispersion relation can be constructed in which the location of saddle points (if they exist) will determine if the flow is convectively or absolutely unstable. This issue cannot be answered in a deterministic way without the aid of stability analysis or highly accurate three-dimensional calculations. Previous research focussed on answering this question has been at best inferential. Success to-date involves the validation of a compressible stability analysis code on previously reported test cases, modifications designed to output the dispersion relation parameters, and the development of a Newton's method approach for identifying dispersion relation saddle points. The latter being significant because it will drastically reduce the required computational effort for identifying the location of the saddle points. This aspect of the research is ongoing and will require the development of an accurate symmetric high incidence base flow.

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Participating Personnel

1. Ms. Shawna M. Davis - B.S.A.E. University of Cincinnati, June 1994. *U.S. Navy Co-Op of the Year 1994* Based in part on her contributions to this work.

2. Mr. Douglas W. Dusing - M.S.A.E. University of Cincinnati, April 1994. Thesis: *On Computing Vortex Asymmetries About Cones at Angle of Attack Using the Conical Navier-Stokes Equations*

3. Dr. Paul D. Orkwis

4. Mr. Raja Sengupta - M.S.A.E. University of Cincinnati, December 1993. Mini-Thesis: *Symmetry Breaking in Vortex Flows Over Slender Bodies - A Review*